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Art. II.—*Three Olivine Basalt-Trachyte Provinces and Some Theories of Petrogenesis.*

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Introduction.

The object of the following pages is to summarize such theories of petrogenesis as afford a reasonable explanation of the evolution of the olivine basalt-trachyte association of the Newer Basalt Series of Victoria (10, 13, 29, 39), the related Older Basalt Series of Victoria, the alkaline lava suite of the Otago Peninsula, New Zealand (4, 31), and the lavas of the Kerguelen Archipelago (14, 25, 34). The rock types comprising the various provinces are tabulated below:—

—	Victoria.		Otago.	Kerguelen.
	Older.	Newer.		
Solvsbergite	+?	+	—	—
Soda-rhyolite	—	—	—	+
Trachyte	+?	+	+	+
Phonolite	+	+?	+	+
Trachyphonolite	—	+	+	+
Trachyandesite	—	+	+?	—
Olivine-trachyte	—	+	+	—?
Trachybasalt	—?	+	+	—?
Oligoclase-basalt*	—?	+	+	+
Andesine-basalt*	—	+	—	+
Labradorite-basalt*	+	+	+	+
Limburgite	+	+	+	+
Olivine-nephelinite	+?	+?	+	—
Basanite	—	—	+	—
Crinanite	+	—	—	—

* Olivine-bearing.

The lavas of the several provinces are characterized throughout by the presence of olivine and of diopsidic pyroxenes, titanaugite (at Otago, Kerguelen, and the Victorian Older Basalts), and aegirine. No pigeonite has been observed or recorded; and tholeiitic rocks appear to be absent.

A particular feature of the rocks of these provinces is the presence of xenocrysts of anorthoclase, and to a less extent, aegirine, in practically all the members of the suite, in such a state of resorption as to indicate that they have returned from conditions of low temperature to conditions of high temperature.

Environments of the Provinces.

The two Victorian provinces are typical " Intra-Pacific " suites, as defined by Washington (45), which have developed in a continental region. The Older Basalt Series, which is probably Oligocene in age, outcrops as scattered remnants over the highlands in the south-eastern, eastern, and north-eastern parts of the State, while the Newer Basalt Series, extruded throughout the Pleistocene and Recent eras, covers broad areas in south-central and south-western Victoria, the younger centres of eruption being mostly in the west, and the older centres in the eastern areas.

In view of the dominant development of andesitic lavas in continental regions that have undergone an immediately previous orogeny, it seems significant that this region was scarcely affected by the Mesozoic and Tertiary fold-movements of the Circum-Pacific zone. It has not experienced a major orogeny since the Devonian period; and the lavas which were extruded in central and eastern Victoria at the close of that period were a series of andesites, dacites, and rhyolites (12, 20, 23, 39), which were accompanied by granodioritic intrusives, and appear to have developed from a basaltic magma by its assimilation of great quantities of argillaceous and siliceous sediments. The amount of sedimentation since the Devonian period has been relatively slight, and the magma giving rise to the alkaline suite of lavas has had to penetrate the same sediments as those penetrated by the andesitic lavas. Emphasis is thus placed upon either the diverse compositions of the original magmas from which the two suites were evolved, or upon their different time relations to orogenic periods, as the factors affecting their contrasted paths of differentiation. The power to assimilate argillaceous sediments might be dependent upon the composition of the primary magma, or, more probably, proximity to the orogenic period may affect the assimilative power of the rising magma owing to pre-heating of the sediments during the orogenesis.

Kerguelen Island is a true oceanic island, situated in the sub-Antarctic region of the Indian Ocean, about longitude 70 deg. E. and latitude 49 deg. S. Mawson (32) has shown it, with Heard and MacDonald Islands, to be "minor sub-aerial features of a vast submarine rise from the floor of the deep Southern Ocean." This ridge has been traced down into Antarctic latitudes, and is suggested to be "an igneous blister on the deep ocean floor, culminating, where marked effusion has taken place, in the several island groups."

The third province cited, the alkaline suite of the Otago Peninsula, South Island, New Zealand, has developed in an area associated geographically with the Tertiary fold-movements which gave rise to the Southern Alps of New Zealand; but there was a period of quiet deposition of sediments ranging from the Upper Cretaceous through to the late Oligocene, followed by slight flexing and faulting, and then regional peneplanation, preceding the extrusion of the lavas, so that, as in Victoria, the pre-volcanic era was a relatively stable one. The Otago area has been complicated, however, by post-volcanic folding and dislocation.

Limestone Desilication.

The theory that alkaline suites may arise from the desilication of basaltic magma through assimilation of calcareous sediments, originally presented by Daly (8), and elaborated by Shand (36, 37), presents many attractive features, but does not provide a general solution of the problem of the olivine basalt-trachyte association (1, 22, 40), and it cannot be applied to the provinces in question.

The Tertiary volcanic rocks of Victoria have risen through a basement in all probability granitic, with overlying Palaeozoic and Mesozoic sediments that are notable for their paucity in limestone or other calcareous types, the prominent rocks being argillaceous shales and sandstones (11, 26). The marine Tertiary beds which locally underlie the basalts, rarely occur within the neighbourhood of the alkaline types. They could not have entered into the differentiation processes, because they are surface deposits, and the differentiation occurred within a magma chamber. If the presence of xenoliths of norite and xenocrysts of rhombic pyroxenes are to be accepted as evidence of assimilation (6, 33, 41, 42), they indicate that the type of sediment assimilated was argillaceous, and that the effect of such assimilation was to direct the differentiation towards andesitic types rather than trachytic, as in the Devonian epoch. Moreover, although the Devonian magmas would have been equally exposed to assimilation of such calcareous sediments as exist at depth, the lavas differentiated from them are practically devoid of alkaline types.

The possibility of the production of trachytic and phonolitic lavas through the assimilation of calcareous sediments by basaltic magmas has been discussed by all who have written about the

Kerguelen lavas, and the weight of opinion is overwhelmingly opposed to it (25, 34, 40, 45). The investigations of de La Rue (34) and of Mawson (32) have shown the island to be almost exclusively igneous in character. The only sediments known to occur are beds of lignite, intercalated with the sheets of basalt, and blocks of *Globigerina* ooze in the volcanic debris. This requires that the differentiation of the lavas was completed before the lavas burst through the thin deposit of ooze on the sea floor; and the presence of *Globigerina* ooze is proof that the sea-depths at the commencement of the lava extrusions were too great for the formation of coral limestones. Mawson's researches indicate that the Kerguelen seas were warmer in Oligocene times than has been supposed (45), but by the time when coral reefs might have formed, the magma chamber would have been completely armoured against them by previously extruded lavas.

The Otago area appears, at first sight, to provide an excellent example in support of the limestone-assimilation theory, since a belt of limestone from 1 to 2 miles wide runs the whole length of the western side of the area—a distance of about 12 miles—giving way at the northern end to a melilite-basanite. However, it is a Tertiary limestone, not greatly older than the lavas, and has a maximum thickness of about 1,000 feet, being underlain by a great thickness or metamorphosed mica schist. The alkaline magma must therefore have been practically differentiated before it came into contact with the limestone, and whatever influence the latter exerted upon it, it could not have been sufficient to initiate the alkaline types. Benson (4) has shown that the differentiation at Otago consists of three repetitive cycles, leading to a triplication of the entire suite. The amount of limestone requiring to be assimilated for such an evolution was not available.

Two Basaltic Parent Magmas.

Kennedy (24) has recently advanced the view that there are two types of parent basaltic magma—the olivine-basalt magma type, and the tholeiitic magma type. Both of these types satisfy him as to their possession of characters essential to a primary basaltic magma—uniformity of composition, world-wide occurrence, great aggregate bulk, and existence as a liquid.

The essential minerals of the olivine-basalt magma type are:—Olivine, calcic pyroxene (diopside, aegirine-diopside, and titanaugite), basic plagioclase, and iron-ores. The tholeiitic magma type bears little or no olivine, and its essential minerals are lime-poor pyroxene (enstatite-augite and pigeonite), basic plagioclase and iron-ores.

In the olivine-basalt line of descent, the variation is either towards a trachytic differentiate, richer in silica than the parent basalt, and with the composition of an alkali syenite, phonolite, or trachyte; or towards a more basic variety, not appreciably more siliceous than the original basalt, and chemically similar to a monzonitic soda-shonkinite or theralite. Further differentiation of these basic alkaline types would give rise to typical phonolites.

The tholeiitic line of descent yields late differentiates unmistakably calc-alkaline in character—chiefly of granodioritic, dacitic or rhyolitic composition, and with a dominance of soda over potash, leading in certain cases to pronouncedly trondhjemitic compositions. Kennedy firmly believes that the highly alkaline types of rock have been produced, not from an originally alkaline magma, nor by any abnormal process of differentiation, but by the ordinary differentiation of a normal olivine-basalt.

The Pyroxene Control in Differentiation.

Lehmann (27, 28) has developed the thesis that the type of pyroxene developed in the original magma controls the nature of the subsequent differentation. Kennedy (24) suggests that the original chemical composition forms the ultimate control, but that the means whereby the end is attained are seen in the species of pyroxene that separate out.

He considers that different species of pyroxene crystallize out from olivine-basalt magma and from tholeiitic magma. From the former come basaltic-augite, diopside, titanaugite, aegirine-augite, and aegirine; from the latter the lime-poor enstatite-augites and pigeonites. This is in opposition to the view of Barth (2, 3) and of Fermor (16), who hold that pigeonite is the common pyroxene of all basalts. Kennedy asserts that Barth, when formulating his hypothesis that crystallization of pyroxenes trends from diopsidic to pigeonitic compositions as differentiation proceeds, has failed to take into account this controlling ability of the original magma; and he points out that, if Barth's view be accepted, the pyroxenes of trachytes should be enstatite-augites, instead of aegirine.

The data in Barth's paper on the "Mineralogy of Pacific Lavas"(2), as shown in the table below, provide excellent support of Kennedy's thesis. Barth has separated the Hawaiian lavas according to Shand's classification (36), into sub-basalts (undersaturated, but not alkaline, which is equivalent to olivine-basalt magma), and basalts (saturated types, equivalent to tholeiitic magma). The value of 2V for the groundmass pyroxenes of the sub-basalts, and pacificites, averages about 50°–60°, with some exceptions, indicating a generally diopsidic character for the pyroxene, while those recorded for the basalts range from 0°–60° generally indicating a more pigeonitic type of pyroxene.

Value of 2V for Groundmass Pyroxenes in Pacific Lavas. By Barth.
(Tabulated from Data by Barth.)

Sub-basalts.	Basalts.	Pacificites.	Basanites.
58°	*30°–40°	58°	60°
50°–60°	*22°	58°	
58°	*40°–50°	56°	
60°–80°	* 0°–54°	56°	
50°	*40°–50°	56°	
56°–60°	*10°–30°	56°	
58°	56°	*20°–40°	
*40°	*40°–50°		
*20°–40°	*30°–60°		
*30°–50°			
56°			
60°			
75°			

* Pigeonitic pyroxene.

Wahl (43), in discussing the factors that control the separation of olivine and calcic pyroxene in the one instance, and of lime-poor pyroxene in the other, came to the conclusion that the original composition of the magma must be the determining factor.

Kennedy (24) explains the mechanism of this control by showing that the composition of the olivine-basalt magma would be such that it would lie well within the stability field for forsterite, as portrayed in the ternary system Forsterite-diopside-silica investigated by Bowen (5), and rather close to the forsterite diopside curve. The crystallization of the magma would commence with the separation of forsterite, and the liquid would be enriched in lime relative to magnesia, so that the lime would crystallize as pyroxene. This would force the alumina to combine with the residual soda and potash, giving rise to alkali-felspars, and eventually to felspathoids.

The composition of the tholeiitic magma, he shows, would lie either close to the boundary of the forsterite stability field, or else entirely within the pyroxene area. No olivine or only a very subordinate amount would separate, and crystallization would commence with the separation of monoclinic pyroxene. The nature of the three-phase boundary is such that this would of necessity be a relatively lime-poor type of enstatite-augite. Thus a larger proportion of the lime would be left free to combine with the alumina than for the case of the olivine-basalt magma, and the plagioclase felspar formed would be correspondingly more calcic.

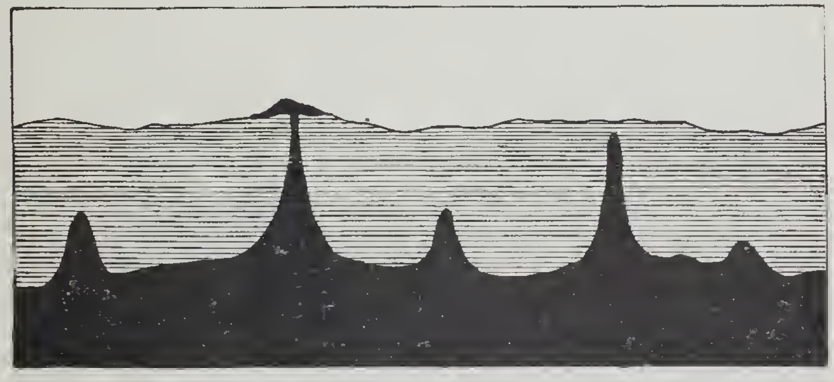
The list of rock types, and minerals, cited upon page 1 shows that the lavas of the three provinces under consideration belong to Kennedy's olivine-basalt magma suite.

Mechanics of Intrusion.

In an unpublished thesis presented for the degree of Ph.D., London (13), the author has noted the tendency, throughout Central Victoria, for parallel cycles of differentiation to develop in restricted localities, at irregular intervals throughout the period of vulcanicity, and of a later widespread outpouring of little-differentiated basalt. To explain this it seems necessary to postulate that the magma rose through the crust as a series of small, steeply-domed, cupola-like bodies, rising at irregular intervals in advance of, but connected with, the main magma reservoir, which is pictured as a sheet-like basin, having much the same areal proportion as the present basaltic plains, as depicted hypothetically in Figure 1.

In these restricted bodies differentiation would be able to proceed as in a laccolith, the acid alkaline fluids being displaced upwards, and concentrated in the upper portions of the cupolas, with a gradation downwards into more basic material. Had the alkaline fluids risen to form merely the upper layer of a great sheet of magma, their small bulk would have been so attenuated as to be thoroughly remixed during the eruptive processes. The composite magma chamber is to be regarded as moving slowly towards the surface; and, since the later extrusions were generally located to the west of the earlier ones, as possibly dragging a little westwards in response to the revolution of the earth, after the manner pictured by Bailey Willis (46) for his "asthenoliths."

The localized and repeated development of trachyte and phonolite bodies at Kerguelen and Otago in association with vast sheets of basalt seems to require a similar form of magma chamber.



Text Fig. 1.—Diagram illustrating the hypothetical magma reservoir, with cupolas developing and rising in advance of it.

An explanation of the origin of such cupolas, and of the mechanism of their ascent through the cooler crust has been devised by Holmes(21) from the principles of convective circulation taken in conjunction with the large difference that exists between the thermal gradients maintained by convection currents, and the much steeper gradients of the rise of fusion temperature with pressure (or depth). The fusion temperature for basaltic magma increases at the rate of about 3°C. per kilometre of depth, whereas in cooling by convection, the gradient which the circulation tends to establish is a downward increase of 0.3°C. per kilometre. The exact figures matter less than the fact that the former rate of increase is about ten times as rapid as the latter. Holmes shows that under conditions of equilibrium the convection gradient would maintain the magma at the top of such a cupola at a temperature well above its fusion point, and so long as the supply of heat from the main reservoir continued, this superheat would impinge against the roof of the cupola, and would be available for supplying latent heat, and for fusing the material of the roof and the sides nearby. The augmented magma and the liberated crystals would be carried down with the return peripheral circulation along or parallel to the enclosing walls. In this way the roof of the cupola would be gradually extended upwards, so long as the supply of heat was maintained. Some modification of the magma would result from the accompanying assimilation, but the greater part of the added material would be carried down into the depths of the cupola, and so distributed throughout the body of the magma. Holmes shows that when this mode of intrusion is coupled with crystallization differentiation, the upper parts of the magma within the cupola would change through a trachybasaltic or oligoclase-basalt (mugearite) composition to a trachytic composition, provided that sufficient time elapsed. In the Victorian provinces the earlier Newer Basalt centres (i.e., areas centred above a cupola) reached the trachytic stage of differentiation, but the later centres did not, in general, advance beyond the oligoclase-basalt stage before extrusion occurred from the cupola. At Kerguelen, and at Otago, the differentiation continued far more frequently as far as the trachytic stage.

Anomalous Alkaline Minerals.

This hypothesis of Holmes also provides a reasonable explanation of the anomalous anorthoclase and aegirine xenocrysts which are sometimes frequent in the Victorian Newer and Older Basalts, and in the rocks of the Otago suite, and sometimes in the Kerguelen lavas, and for the large anorthoclase, alkali-rich hornblende, and pyroxene crystals found in the tuff beds and scoria cones of the Western District (30).

In the unpublished thesis previously cited (13) I have described evidence believed to be recorded for the first time, which indicates that the anorthoclase phenocrysts in the Victorian trachytes represent a potential "anorthoclase rock". The "phenocrysts" consist of small intergrown crystals of anorthoclase, which crystallized before the other materials of the trachytes, and appear to have floated upwards in the magma. But despite this, anorthoclase crystals, or aggregates of them, are found in practically every rock type in the province, even in the limburgites, with this difference—that the more basic the rock type, the greater the degree to which the anorthoclase crystals have been resorbed, i.e., are out of equilibrium with the containing magmas.

Similarly aegirine, which in the trachytic rocks is a late product of crystallization differentiation, is found as occasional, and always much larger, crystals in the numerous more basic types, and especially in the limburgites. Such aegirine crystals are generally much resorbed, and are always armoured about with a rim of diopside. Some even contain a core of diopside of earlier age than the main aegirine crystal, as well as the later rim. It is thought that these large aegirine crystals crystallized at the same time as the anorthoclase crystals, but being much heavier, sank, whereas the anorthoclase crystals rose. On account of their sinking many more of them were completely resorbed in comparison with the anorthoclase crystals, so explaining their fewer numbers.

There is thus evidence that these crystals have passed from low-temperature conditions back to high temperature conditions. If gravitational settling is excluded for the anorthoclase crystals, as it would seem to be, then the explanation of their habits may be given by Holmes' hypothesis, the anorthoclase and aegirine being carried downwards through the peripheral regions of the cupola by the convection currents, and so back finally into the central and hot regions, where they dissolved, unless armoured about by high temperature minerals. During extrusion the upsurge of the magma would proceed more rapidly in the more fluid central regions of the cupola than in the cooler peripheral regions, and much of the crystalline material might be caught up and brought to the surface as cognate xenocrysts.

This hypothesis requires that the "trachytic and phonolitic magmas" should be concentrated at the top of the cupola, and also in the upper peripheral regions; and so, although trachytes may be expected among the earliest of the extrusives types from any cupola, it is quite possible that more basic magma from the central part of the cupola, being more fluid than the cooler and partly crystalline alkaline magma in the peripheral parts, might be extruded more rapidly. This would provide an explanation of the variable sequence of extrusion such as has developed at

Macedon (Victoria), where the order of extrusions appears to have been (1) solvsbergite; (2) oligoclase-basalt; (3) anorthoclase-trachyte; (4) anorthoclase-basalt; (5) olivine-trachyte.

Trachyandesite and Norite.

Trachyandesite.

The presence of hypersthene in certain rocks is commonly accepted as evidence of assimilation of argillaceous rocks (6, 33, 41, 42). Holmes (21) has shown that local fusion of sediments associated with the penetration of cupolas into the granitic layer of the crust may result in the formation of small bodies of acid magma above the cupolas. Such local bodies of magma will become increasingly mixed with the ascending magma as the cupola rises.

At Coliban, in Victoria, there occur glassy trachyandesites with as much as 63 per cent. of silica, which yet contain remnants of olivine. They also carry orthorhombic pyroxenes which are in a semi-resorbed state, while monoclinic pyroxenes are seen in the act of crystallizing; and it is suggested that these rocks may have originated in such a manner.

Norite.

Xenoliths of norite in the basalts indicate that there may be norite bodies at depth, and these, and the corroded crystals of orthorhombic pyroxene found as xenocrysts in many of the basalts, are thought to have been derived from the assimilation of argillaceous sediments which must have accompanied such cupola intrusion.

Gaseous Transfer.

The alternative processes which lead to the development of trachyte on the one hand, and to phonolite on the other, require explanation. Somewhat parallel alternative products were obtained by Bowen, Schairer, and Willems (7), arising out of fractional crystallization, during their study of the ternary system Sodium silicate-ferric oxide-silica; but this did not make clear the cause underlying such fractionation. A possible cause lies in the suggestion made by Smyth (40), and elaborated by Shand (37), that sodic material is especially liable to gaseous transfer.

Olivine-basalt magma, under stable and undisturbed conditions, differentiates towards trachyte; but as soon as the roof of the magma chamber is fractured, and extrusion has commenced, the conditions within the chamber are altered. Previously the volatiles had exerted a considerable pressure against the walls of the reservoir, a pressure equally distributed over the chamber. With the sudden and localized release of pressure, the severely compressed volatiles would expand, with the result that bubbles of gas would develop throughout the magma and stream towards the vent. The result of release of pressure in a soda-water syphon may be suggested as an analogy. If these volatiles are carriers of soda, then a concentration of soda should develop in the upper part of the magma chamber, and trachytic differentiates should give place to phonolitic types. The irregular concentration of soda in crinanites (9, 15, 44) is evidence in favour of this mobility of sodic material, independently of normal differentiation processes; and Gilluly (17, 18) has described much evidence of the independent movement of soda (i.e., independent of potash and lime) with the fugitive (gaseous and liquid) elements of granitic magmas.

Some such hypothesis seems necessary if one is to explain why trachytes are among the early alkaline types at Otago, and probably, at Kerguelen, while the later alkaline lavas are generally phonolitic.

Provided that a magma is rich in volatile constituents, extrusion ushers in a period of oxidation. The volatiles are released, and stream through the magma towards the vent, being relatively concentrated as they approach the vent, and so exposing that part of the magma to an intensified reaction with them. Thus pyroxene crystals are observed in the trachytes and phonolites, reacting to form aegirine and iron-ore. Soda-rich liquid would not be sufficient of itself to bring about this reaction; oxidation of the ferrous iron of the diopside to the ferric state is essential for the formation of aegirine.

But the most marked evidence of this period of oxidation is shown in basalts, where the oxidation leads to the development of rims of iddingsite about their olivine crystals. This development of iddingsite is a feature of Victorian and some Kerguelen and Otago basalts, and in the Victorian rocks there is evidence to suggest that a discontinuous series exists under such conditions of oxidation, whereby olivine is replaced by iddingsite, and iddingsite by iron-ore. Thus:—

Olivine.	→	Iddingsite.	→	Iron-ore.
$2(Mg.Fe)O.SiO_2$		$MgO.Fe_2O_3.3SiO_2.4H_2O$		$FeO.Fe_2O_3$

For the first stage at least, vigorous oxidation, and the presence of water vapour are essential.

This appears to be an expression of the reaction:—

$$H_2O + 2FeO = H_2 + Fe_2O_3$$

which is stated by Goodchild (19) to be isothermal, and delicately balanced. The concentration of water vapour at the vent during extrusion would drive the action from left to right, and the precipitation of ferric oxide in iddingsite, further unbalancing the equation, would speed up the reaction in this direction; but once the magma had been extruded as lava, and was freed from water vapour, the reverse action might be expected to set in. Evidence for this reversal has been found in the Victorian basalts (13), where in some instances, later rims of olivine have developed about crystals which had been partially or completely altered to iddingsite. Similar features have been recorded by Ross and Shannon (35) for American basalts, although they were not interpreted in this manner.

Summary.

Investigation of the olivine-basalt-trachyte association in the Tertiary igneous provinces of Victoria, Kerguelen Island, and Otago, New Zealand, supports the theory that alkaline rocks are the normal product of differentiation of an olivine-basalt magma, so long as there is no undue amount of contamination by contemporary syntexis; and that the factors controlling the differentiation are:—

1. The chemical composition of the primary magma, acting through the type of pyroxene that is able to crystallize from it.
2. The growth of cupola-like extensions above the main magma reservoir, permitting the accumulation of alkaline magma in sufficiently concentrated, localized bodies.
3. The oxidizing conditions ushered in by the development of gas streaming during extrusion, and the transport of sodic material accomplished by such streaming.

In the absence of an immediately previous orogeny such alkaline rocks will develop in a continental (sialic) region as readily as in an oceanic (semic) region; but an orogeny provides conditions favorable to large scale assimilation of argillaceous and siliceous sediments, with an accompanying production of andesitic types.

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